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14. ABSTRACT

The long-term goals of the research under this award have been to discover and understand generic phenomena in a whole class of vortex-induced vibration systems. We discover, using novel controlled damping, that the immense scatter in the classical Griffin plot (peak amplitude versus mass-damping) over 3 decades, can now be collapsed beautifully if one renormalises the axes, taking into account the effect of Reynolds number, which was previously not considered. We find, from controlled vibration of a cylinder, using extremely high-resolution variation of parameters, that, for the first time, accurate prediction of vortex-induced vibration is possible by searching for stable solutions with positive excitation. We discover that rising bodies do not vibrate unless their mass falls below a special value, which coincides with critical mass found in VIV studies of elastically mounted bodies. Similar response branches are found for a wide set of VIV systems, and in all studies we find the existence of a critical mass. Our work has formed the basis of a number of comprehensive papers in *Journal of Fluid Mechanics* and other journals, and has led to an invited review of VIV in *Annual Review of Fluid Mechanics (2004)*. The P.I. has founded and chaired a series of international conferences on *Bluff Body Wakes and Vortex-Induced Vibrations* (USA in 1998, France in 2000, Australia in 2002, Greece in 2005, Brazil in 2007).

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FINAL REPORT OF RESEARCH ON ONR GRANT

N00014-04-1-0031

"VORTEX-INDUCED VIBRATION: UNIVERSAL PHENOMENA IN DIVERSE SYSTEMS"

P.I. C.H.K.WILLIAMSON

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The long-term goals of the research under this award have been to discover and understand generic phenomena in a whole class of vortex-induced vibration systems. We have studied the motion of flexible bodies, as well as induced forces due to the corresponding wake vortex dynamics, in the presence of currents and waves in the ocean. We have studied the fundamental mechanisms involved in the interaction of current with axisymmetric or cylindrical bodies, including both rigid and flexible structures, which are tethered or free (restrained or unrestrained) to respond to the fluid forcing. We have investigated the in-line and transverse dynamics and forces, wake vortical motions, and signatures of such bodies undergoing vortex-induced vibrations (VIV). We are interested in comparing predictions based on (very high resolution) controlled vibration, versus measurements from free vibration, and building up a profound understanding of the forcing and vortex dynamics responsible for fundamental steady state and transient free vibration phenomena.

This award has been used to support a number of students at different periods of their study, and has been instrumental in training them in their PhD programs. The award has been very effective in providing a cohesive research group with sufficient critical mass to move rapidly forward in the research program. The award has been used to support wholly or in part a large number of research publications which are listed at the end of this Final Report.

Our major emphasis with this work has been (and continues to be) the combined study on a number of diverse vortex-induced vibration problems, with a major goal of discovering universal characteristics of such systems. We have completed a large set of studies, some of which are published in *Journal of Fluid Mechanics* and *Journal of Fluids and Structures*, amongst other journals, and are listed in the Publications section later. The support of the Ocean Engineering Area of the Office of Naval Research for both our research, and that of other groups, has directly led to significant steps forward in this field, and the field has progressed far beyond our understanding of one decade ago, mostly encouraged by new techniques in computation and experiment, and also from the study of much lower mass and damping than were hitherto studied. These new results are discussed by the PI comprehensively in an invited review paper, "Vortex-Induced Vibrations" (Williamson & Govardhan, 2004 volume of *Annual Review of Fluid Mechanics*). We should mention also that this has been followed in 2005-6 by three invited plenary presentations on the work done in this award period.

The objectives of this research program, involving multiple related projects, has continued to evolve as newer projects have received more focus in our research program, over the period of this award. Firstly, we have investigated the response and forcing on elastically-mounted rigid and flexible bodies (cylinders) in a current, with increased emphasis more recently on the effects of Reynolds number. We continue to further understand resonance phenomena and the relation between forcing and wake-vortex dynamics for bodies with one and two degrees of freedom. A second area of research, which has recently received much impetus in our program, involves the rising and falling of bodies, since this has a fundamental connection with phenomena concerning elastically-mounted structures. A third component of the research has been the study of the dynamics of tethered bodies (spheres) in currents, to discover periodic oscillation modes, and the relationship between the dynamics, the forcing and the wake vortical dynamics/signatures. The fourth objective of the research has been to understand the vortex-induced vibration of bodies which have a spanwise variation of amplitude, such as for a flexible cylinder, or the simpler case of a pivoted cylinder, both of which examples allow two-degree of freedom dynamics. Finally, our fifth objective, and perhaps the most significant, has been to uncover generic phenomena for a whole class of VIV systems.

It should be mentioned that in all of our studies up to this point, we have employed the simultaneous measurement of displacement, force and vorticity, and this constitutes the first time such a simultaneous approach had been used in free vibrations (see Khalak & Williamson, 1997;1999; Govardhan & Williamson, 2000). We have been using extensively the Cornell-ONR Water Channel, for the primary experiments involving flow-induced vibrations. We have also been using the computer-controlled X-Y Towing Tank for detailed visualisation and force measurements for bodies in steady/unsteady motion.

One recent publication (Govardhan & Williamson, 2006, *Journal of Fluid Mechanics*) has resulted from our capabilities to design methods to impose both positive and *negative damping* upon our VIV system comprising an elastically-mounted cylinder. This has enabled us to undertake a careful study to understand the effects of Reynolds number on peak vibration response in VIV, in a systematic and highly sensitive manner. The effects of Reynolds number has not widely been considered in such VIV systems. Our controlled-damping techniques employ both eddy current damping as well as a simple but effective method using a spring force, applied in phase with the instantaneously measured velocity in the system.

We have further developed two vertical water tanks, with glass sides to permit the launching of rising and falling bodies through the fluid. At this point, we have the means with these facilities to measure optically the 3D dynamics of spheres, and the dynamics of horizontal cylinders, as they rise or fall (depending on whether the relative density is below, or exceeds, unity). These studies yield novel and interesting results, relating strongly (and fortunately quite consistently) with the VIV of elastically-mounted or tethered bodies.

We have been able to precisely measure the dynamics of the bodies (in the case of the sphere, with two coordinated cameras from orthogonal directions), although it is very difficult to determine the vorticity and fluid forcing on the bodies in the vertical tanks. We have therefore embarked on the idea of translating bodies in the computer-controlled XYθ Towing Tank for a body moving in the identical trajectories that we have measured in the vertical tanks, so to measure the vorticity and fluid loading directly and much more efficiently. We have also been experimenting with fluids of different viscosity in the vertical tanks, to achieve required values of Reynolds numbers, since this has proven easier than assembling a large number of different-sized bodies. In the vertical tanks, we have developed a technique of flow visualisation, which is proving highly effective, using Laser-Induced Fluorescence in both floodlight and thin sheets, to investigate the relation between modes of motion, and visualisation of vortex dynamics, for the rising or falling bodies.

We have made substantial progress on these projects funded by the ONR, leading to some new discoveries, and to a large number of refereed journal publications (please see Publications List). In the period of this award, we have explored the rich phenomena for VIV of cylinders and other bodies, at extremely low mass and damping. Our series of experiments has enabled us to make some fundamental new discoveries concerning vortex-induced vibration.

Previous experiments over the last 30 years indicate a large scatter in peak amplitude data (A^*) versus the product of mass-damping (α), in the so-called "Griffin plot". A principal result in the present work is the discovery that one can collapse the data very well if one takes into account the effect of Reynolds number (Re), as an extra parameter in the Griffin plot. This work has been published in *Journal of Fluid Mechanics* (Govardhan & Williamson, 2006). In our work, a key to the discovery of the systematic influence of Reynolds number (Re) on the classical Griffin plot has been our successful implementation of a means to *control both positive and negative damping* in our experiments on a freely-vibrating body. One of our deductions which has allowed us to collapse the widely scattered data in a typical Griffin plot, is to realise that the data is well represented by separating the variables $\{\mathrm{Re}, \alpha\}$, in the manner:

$$A^*_{PEAK} = f\{\mathrm{Re}\} \,.\, g\{\alpha\}$$

where, for constant values of Reynolds number, the peak amplitude is proportional to $g\{\alpha\}$:

$$g\{\alpha\} = 1 - 1.12\alpha + 0.30\alpha^2$$

We also show that data from our experiments, and from previous studies for very lightly-damped systems, over a wide range of Re = 500 - 33,000, indicates that the peak amplitude data increases nearly linearly versus a logarithmic Reynolds number axis:

$$f\{\mathrm{Re}\} = \log(0.41\mathrm{Re}^{0.36})$$

It is this key result which enabled us to collapse widely scattered data in the Griffin plot onto a single curve, given by an equation for the "modified amplitude", A^*_M:

$$A^* = (1 - 1.12\alpha + 0.30\alpha^2)\log(0.41\mathrm{Re}^{0.36})$$

in the "modified" Griffin plot (in Govardhan & Williamson, 2006, *Journal of Fluid Mechanics*).

In further fundamental studies, we have proven that if the mass of a vibrating body falls below a critical value, then the large-amplitude resonant oscillations of the system persist up to infinite flow velocity (Govardhan & Williamson, 2000 and 2002, *Journal of Fluid Mechanics,* Horowitz & Williamson, 2006, *Journal of Fluids and Structures*). As predicted in the 2000 paper, the unrestrained experiments indicated a substantial amplitude *only* when the mass falls below a special value, dependent on the body.

Concerning generic phenomena, we have been able to show that, for all VIV system geometries we have investigated, there exists a critical mass, when there is a catastrophic jump in the response of the system to vortex-induced forces. Further to this, we show that the critical mass should be a feature of all such VIV systems, governed approximately by the same type of equations of motion, and is therefore a generic phenomenon in VIV systems. We have measured the critical mass for several VIV systems (Govardhan & Williamson, 2005, *Journal of Fluid Mechanics*; Flemming & Williamson, 2005, *Journal of Fluid Mechanics*; Jauvtis & Williamson, 2004, *Journal of Fluid Mechanics*) and for all the physically distinct cases so far, it seems to be close to 0.5 - 0.6. The underlying reason for the coincidence of values is a challenging question which remains unanswered presently, and it is of significance to understand, since it has such a practical impact for VIV systems. Our ongoing approach using the high resolution controlled vibrations experiments will certainly contribute to the understanding of this phenomenon, amongst others.

The case of completely free bodies, such as cylinders or spheres allowed to rise or fall freely, has had almost no prior investigation. One key result, coming from our research, is the fact that the body does not vibrate when it falls, whether it be a cylinder or a sphere. However, when the body rises, one has to reduce the mass to a certain threshold value, until suddenly the body jumps into periodic vibration!

In the case of the rising cylinder, this special threshold value of relative density for the cylinder is 54% ! It is the same value of critical mass for which elastically-mounted cylinders exhibit large-amplitudes up to infinitely-high velocities. When $m^*<0.54$, the completely unrestrained body takes on a 2P vortex wake mode (two vortex pairs per cycle), similar to that for the elastically-mounted case, and thus *appears* to be consistent with the agreement in values of critical mass for the two cases.

In order to interpret how vorticity dynamics actually leads to body vibration, we have qualitatively interpreted the principal vortex dynamics and vortex forces which yield a positive rate of energy transfer (de/dt) causing the body vibration, using a simple relation, following the study by Jauvtis & Williamson (2004, *Journal of Fluid Mechanics*), where simultaneous force and vorticity motions were measured. In a nutshell, one has a positive rate of energy transfer into the transverse vibration, when a clockwise vortex travels downstream, while the body is moving downwards (or similarly, when the body is moving upwards in the presence of a dominant anti-clockwise vortex). These simple ideas have been used to interpret the manner in which the 2S, 2P and 2T vortex wake modes cause vibration, and they will help to understand concepts when the direct full vorticity - force relations are implemented in the future.

An interesting correspondence between unrestrained body dynamics, and the motion of elastically-mounted bodies, is the case of the freely rising or falling cylinder. The unsteady trajectories for the rising bodies, in Lissajou figures, are quite different from those of a 2-degree-of-freedom elastically-mounted cylinder at higher mass ratios. There are also differences in the vortex mode. We suggest that these differences are a mass ratio effect - with the rising cylinder we are able to explore much lower mass ratios than is possible with the elastic body. In fact, since the 2 DOF flow is influenced by the independent variation of mass rather than mass-damping (unlike the Y-motion only elastic body experiments), these rising body experiments are indicating a new response branch and vortex mode to be expected from 2 DOF elastic systems, if one could attain sufficiently low mass. By considering the equations of motion, one major deduction is that *the rising cylinder is completely equivalent to a 2-degree-of freedom elastically-mounted system* where we have zero damping, and where the springs are removed, such that we are effectively considering very large normalised velocity U^*. These experiments thus determine accurately the critical mass for an equivalent 2 degree-of-freedom elastic system. These results form a component of a paper (Horowitz & Williamson, 2007, for *Journal of Fluid Mechanics*).

In the studies on the rising and falling bodies, the spheres exhibit a critical mass of around 61%, consistent with the tethered sphere studies of Govardhan & Williamson, 2005, *Journal of Fluid Mechanics*). This phenomenon, for any rising 3D body (immiscible fluid or solid), where it does not vibrate unless below a certain relative density, is a novel result in this field of research. The result contrasts with the general belief presently held in the literature that *all rising bodies vibrate, and all* *falling bodies do not vibrate.* This general belief is not correct. Also in contrast to previous work, we find no evidence of spiralling trajectories, observing only vibrations in a vertical plane. These results are to be presented at the *American Physical Society* meeting (Salt Lake City, Nov 2007).

From careful fluorescent flow visualisations, we have discovered that the rising and vibrating sphere exhibits a fascinating 4-vortex ring mode, quite unlike any vortex mode that develops behind fixed spheres, and this new result was presented at the *American Physical Society* meeting, Chicago, Nov 2005 in the PI's invited plenary lecture. Interestingly, this 3D mode involving vortex rings has an analogy with the two-dimensional vortex mode for rectilinear vortices behind cylinders undergoing VIV, namely the 2P mode.

In ongoing work, we have been able to measure optically the trajectories of the bodies, and to impart such identical motion to a much larger-scale body in our computer-controlled XYθ Towing Tank. By imposing much lower velocities, we can in essence, *keep the Reynolds number the same as in the freely rising case.* This allows us to study, with large-scale precision, the vortex dynamics, by employing the combined approach of LIF visualisation, along with PIV measurements of velocity and vorticity. The use of two quite different facilities is proving to be a significant and useful approach. All of the above results will form a component of an upcoming paper (Horowitz & Williamson, 2007, for *Journal of Fluid Mechanics*).

Strongly related with these studies above, are our investigations on the dynamics of tethered spheres (Govardhan & Williamson, 2005, *Journal of Fluid Mechanics*). The spheres are induced into vibration by dynamics of streamwise vorticity, rather than by vorticity normal to the flow. In fact, one can relate the forces to the vortex dynamics by using considerations based on aircraft wake vortex studies, to predict sphere forces to reasonable accuracy. The equation for the vortex force coefficient (C_{VORTEX}), is related very simply with the advection speed of the vortices downstream (U^*_V), the vortex spacing (b^*) and the vortex circulation (Γ^*), given by:

$$C_{vortex} = \frac{8}{\pi} U_v^* b^* \left(-\Gamma^*\right)$$

In a further recent publication (Flemming & Williamson, 2005, *Journal of Fluid Mechanics*), we have studied the dynamics of pivoted rods, with two degrees of freedom, in a free stream. We found that this system not only produced a special "Hybrid *2S-2P* mode" (as found for vibrating cones by Techet et al, 1998), but for light systems, we discovered a very high amplitude branch to be caused by a new "2C mode", which corresponds with a pair of co-rotating vortices per half cycle. When the system has a large amplitude, and the free stream velocity is gradually varied, we find interesting jump phenomena between branches of response. Use of the Hilbert Transform in these dynamics problems has shown that the system intermittently jumps between response branches, or is hysteretic. Interestingly in this case the lower branch of amplitude intersects with the upper branch , yielding apparently the same experimental conditions. However, *the key to the difference in the branches where they intersect is only clear when one takes into account the streamwise motion*, which is distinctly larger for the upper branch system.

Recently, we have been pushing ahead, with a great deal of activity, on a study of controlled vibrations where we have first demanded of our system an *extremely high resolution* in the variation of amplitude and frequency of vibration. (Our cylinder was suspended vertically in a water channel, and oscillated sinusoidally transverse to a free stream, at a fixed Reynolds number). For one of our Reynolds numbers, a total of 5680 runs have been conducted, for approximately 500 hours worth of data! This is only possible in a continuously flowing (ONR-Cornell) water channel facility and thus could be automated and run unattended for days. The water channel avoids the problems of short run times in a towing tank, and the long wait between runs which plagues towing tank studies.

A second principal point in these experiments is our essential need to *very carefully match the amplitude, frequency, and Reynolds number of the controlled system with elastically mounted cylinder system*. The impetus for these experiments has come from the fact that in previous comparisons with sparse data, it has not proven possible to predict or understand free vibration accurately - indeed, sparse data has led to predictions of response in a whole regime where free vibration does not occur! At low mass and damping, the excitation to balance the energy dissipation is small, and so the phase of the fluid force is also small, thus the precise measurement of phase and force is very important.

For our controlled vibration force contours, we find transitions in certain regions of this plane of amplitude-frequency, where the character of the fluid forces changes between distinct modes. Interestingly, these transitions correspond well with boundaries separating different vortex shedding modes in the Williamson-Roshko (1988) map of regimes. A further new characteristic, which is only observable with very high-resolution data, is the existence of regimes where two modes overlap. We are also able to predict the response of an elastically mounted cylinder that agrees well with the measured free vibration response of Govardhan & Williamson (2006) at both high and low mass-damping. Furthermore, by looking at the shape of the excitation contours and the transitions between different modes, we are even able to explain the mode jumps and the transient behaviour. Good agreement between predictions of vibration, versus free vibration measurements, has been made in preliminary studies (Morse & Williamson, 2006 *Journal of Fluids and Structures*), but will also form papers for submission to *Journal of Fluid Mechanics*. This is an ongoing study.

In conclusion, these fundamental studies of fluid-structure interaction have direct application to the dynamics, wakes and surface signatures of tethered or free near-surface bodies, to cables, and to ocean engineering structures subject to fluid-structure interactions. Rising and falling body studies have a remarkable association with the results of studies with elastically-mounted bodies. For sufficiently light elastic structures, a very wide regime of flow speeds can lead to resonant vibrations of structures, which is of practical significance. Results so far indicate that the critical mass leading to such phenomena is around 50%-60% of the displaced fluid mass, irrespective of the particular VIV system. The character of VIV, and the response branches and vortex dynamics modes, appear to occur over a wide range of Reynolds numbers, although work should be pursued up to higher Reynolds numbers. Our work, regarding the importance of Reynolds number on the Griffin plot, needs urgent attention at higher Reynolds numbers. Finally, we anticipate that our very high-resolution study of controlled vibration will lead to a more profound understanding of VIV phenomena.

Most of the results of our research have been included in several publications which have been placed in the List of Publications. Our work has been presented at several major conferences, and has formed the basis of papers in *Journal of Fluids and Structures*, *Journal of Fluid Mechanics* as well as *J. Wind Engineering and Industrial Aerodynamics*, as well as our invited review paper in *Annual Review of Fluid Mechanics*. Invited presentations and conference seminars have been presented, and the PI has been Co-Chairman (and founder) of a <u>series of conferences bringing together many of the world's leading researchers in this field of research</u>; to Washington, D.C., for the *Conference on Bluff Body Wakes and Vortex-Induced Vibrations* (3 days - 67 seminars), *BBVIV-1* (1998); to Marseille, France, *BBVIV-2* (2000); to Port Douglas, Australia, *BBVIV-3* (2002); to Santorini, Greece, *BBVIV4* (2005) and soon to Costa do Sauipe, Brazil *BBVIV5* (2007). Support in the publication of the Proceedings Volumes came from ONR. It is certainly true that much of the recent impetus over the last decade in this field has arisen due to the support from ONR.

During the period of this award, the P.I has received a number of honours, which are related to the past research conducted under the support of ONR, as follows:

The P.I. has been selected as the *2006 Professor of the Year* for New York state, by the *Carnegie Foundation*, and invited to meet Senator Clinton at the Senate buildings in Washington DC.
The P.I. was awarded the *Astor Visiting Lectureship* at Oxford University in Trinity term, 2006.
The P.I. has been invited to present a Plenary lecture at the *IUTAM Symposium on Unsteady Separated Flows*, Corfu, Greece, June 2007.
The P.I. was an Invited Plenary speaker at the *Canadian Symposium on Fluid Dynamics* (CAIMS-MITACS) in June 2006.
The P.I. was an invited Plenary speaker at the *American Physical Society* meeting in Chicago, Nov 2005.

PUBLICATIONS

WHICH HAVE RESULTED FROM WORK IN WHOLE OR IN PART ON O.N.R. GRANT
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Invited REVIEW PAPERS - *Annual Review of Fluid Mechanics*

C. H. K. Williamson and R. Govardhan (2004) "Vortex-Induced Vibration", *Annual Review of Fluid Mechanics*, **36**, 413 - 455.

Invited REVIEW PAPERS (Other Journals)

C. H. K. Williamson and R. Govardhan (2007) "A brief review of recent results in vortex-induced vibration", Invited Review in special edition on "Bluff Body Aerodynamics and Applications" *J. Wind Engin. and Industrial Aerodynamics*, In press, **95**, Issue 12.

C. H. K. Williamson and R. Govardhan (2004) "A review of recent results in vortex-induced vibrations", Invited Review in *Proc. 5th Int. Colloquium on Bluff Body Aerodynamics and Applications*, 59-75, National Research Council, Canada.

Invited BOOK CHAPTERS:

C. H. K. Williamson (2007) Comprehensive Handbook Chapter: "Bluff Body Aerodynamics", for *Handbook of Experimental Fluid Mechanics,* ed. C. Tropea, J. Foss, & A. Yarin. Book to published by Springer-Verlag, Berlin, Germany. Chapter of 40 pages.

SPECIAL EDITOR OF JOURNAL VOLUMES :

T. Leweke & C. H. K. Williamson (2006) Editors of "Special issue on bluff body wakes and vortex-induced vibration-BBVIV4.", *Journal of Fluids and Structures*, Volume **22**, 261 pages.

T. Leweke, K. Hourigan & C. H. K. Williamson (2004) Editors of "Special issue: Bluff body wakes and vortex-induced vibration.", *European Journal of Mechanics B-Fluids*, Elsevier, Volume **23**, 239 pages.

REFEREED JOURNAL PAPERS -

R. Govardhan and C. H. K. Williamson (2006) "Defining the "modified Griffin plot" in vortex-induced vibration: revealing the effect of Reynolds number using controlled damping", *Journal of Fluid Mechanics*, **561**, 147-180.

M. Horowitz & C. H. K. Williamson (2006) "Dynamics of rising and falling cylinders", *Journal of Fluids and Structures*, **22**, 837-843.

T. Morse & C. H. K. Williamson (2006) "Employing controlled vibrations to predict fluid forces on a freely vibrating cylinder", *Journal of Fluids and Structures*, **22**, 877-884.

F. Flemming and C. H. K. Williamson (2005) "Vortex-induced vibrations of a pivoted cylinder", *Journal of Fluid Mechanics*, **522**, 215-252.

R.Govardhan and C. H. K. Williamson (2005) "Vortex-induced vibrations of a sphere", *Journal of Fluid Mechanics*, **531**, 11-47.

R. Govardhan & C.H.K. Williamson (2004) "Frequency response and the existence of a critical mass for an elastically-mounted cylinder", In *Integrated Modelling of Fully Coupled Fluid Structure Interactions using Analysis, Computations and Experiments*, (ed. H. Benaroya and T.J. Wei), Kluwer.

C. H. K. Williamson & C. Cerretelli (2004) "Merging of a vortex pair", *Advances in Turbulence X*, (ed. H. Anderson and P.-A. Krogstad), Kluwer, 625-628.

N. Jauvtis & C. H. K. Williamson (2004) "The effect of two degrees of freedom on vortex-induced vibration at low mass and damping", *Journal of Fluid Mechanics*, **509**, 219-229.

R. Govardhan and C. H. K. Williamson (2004) "Frequency response and the existence of a critical mass for an elastically-mounted cylinder ", *European Journal of Mechanics B/ Fluids*, **23**, 17-29.

J. Carberry, R. Govardhan, J. Sheridan, D.O. Rockwell & C. H. K. Williamson (2004) "Wake states and response branches of forced and freely oscillating cylinders", *European Journal of Mechanics B/ Fluids*, **23**, 89-99.

C. H. K. Williamson & N. Jauvtis (2004) "A high-amplitude 2T mode of vortex-induced vibration for a light body in XY motion", *European Journal of Mechanics B/ Fluids*, **23**, 107-114.

N. Jauvtis & C. H. K. Williamson (2003) "Vortex-induced vibration of a cylinder with two degrees of freedom", *Journal of Fluids and Structures*, **17**, 1035-1042.

<u>INVITED KEYNOTE ADDRESSES</u> AND <u>INVITED PRESENTATIONS</u>:

C. H. K. Williamson (2007) "Control of vortex dynamics in flow-induced vibration", Opening Plenary Speaker at the *IUTAM Symposium on Unsteady Separated Flows and their Control*, Corfu, GREECE. April 2007.

C. H. K. Williamson (2007) "Discoveries in Vortex-Induced Vibrations", Invited Seminar *RPSEA - Effect of VIV in Oil and Gas Operations*, 11 Jan 2007, Houston, Texas.

C. H. K. Williamson (2006) "Synergy between teaching and research" University-wide lecture as the *Astor Visiting Lectureship*, Oxford University, ENGLAND, 27 April 2006.

C. H. K. Williamson (2006) "Vortex dynamics and instabilities", Invited Plenary Speaker at the *Canadian Symposium on Fluid Dynamics (CAIMS-MITACS Conference)*, York University, Toronto, CANADA, 15-20 June 2006.

C. H. K. Williamson (2005) "New Phenomena in Vortex-Induced Vibrations", Invited Plenary Lecture in the *American Physical Society* Meeting, Chicago, USA, 20-22 Nov 2005.

C. H. K. Williamson (2004) "Recent results in Vortex-Induced Vibrations", Invited Plenary seminar (one of four) for *FIFTH International Conference on Bluff Body Aerodynamics and Applications, (BBAA-V)*, 11-15 July 2004, National Research Council, Ottawa, CANADA.

C. H. K. Williamson (2003) "New results in Vortex-Induced Vibrations", Invited Seminar (one of five) for *Conference on Vortex-Induced Motion (SPAR)*, 3 Days in Oct 2003, Houston, Texas.

<u>CONFERENCE PAPERS</u>

M. Horowitz & C. H. K. Williamson (2007) "Dynamics and wake patterns of rising and falling spheres". *Proc. 5th Conf. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV5*, Costa do Sauípe, BRAZIL, 12-15 Dec. 2007.

T. L. Morse & C. H. K. Williamson (2007) "Understanding mode transitions in vortex-induced vibration using controlled vibration". *Proc. 5th Conf. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV5*, Costa do Sauípe, BRAZIL, 12-15 Dec. 2007.

M. Horowitz & C. H. K. Williamson (2007) "Dynamics and wake patterns of freely rising and falling spheres at Re = 500". *Bull. American Physical Society*, **52**, Gallery of Fluid Motion.

M. Horowitz & C. H. K. Williamson (2007) "Evolution of wake vorticity structures causing vibration of freely rising spheres". *Bull. American Physical Society*, **52**, KT1.

T. L. Morse & C. H. K. Williamson (2007) "An investigation of wake mode transitions and amplitude jumps in vortex-induced vibration using controlled vibration". *Bull. American Physical Society*, **52**, KT2.

T. L. Morse & C. H. K. Williamson (2006) "Understanding mode transitions in vortex-induced vibrations of a circular cylinders using controlled vibration", *Bull. American Physical Society*, **51**-9, 101.

M. Horowitz & C. H. K. Williamson (2006) "Critical mass and vortex dynamics for rising and falling spheres", *Bull. American Physical Society*, **51**-9, 75.

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